The **RESEARCH LABORATORY** *of* **ELECTRONICS**
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
77 MASSACHUSETTS AVENUE
CAMBRIDGE, MASSACHUSETTS 02139-4307

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Dr. Peter J. Reynolds
Program Officer, ONR 331
Office of Naval Research
Ballston Centre Tower One
800 North Quincy Street
Arlington, VA 22217-5660

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Thank you. Please contact me if you have any questions or comments.

Mary S. Greene
RLE Financial Assistant, Room 36-437

cc: Prof. Pritchard (1)
Alex Cronin, 26-229
ACO, Boston, MA
A.F. Favaloro, E19-750
File (1)

OSP 6431200

Enclosures

Room 36-437 ♦ Telephone: (617) 253-8139 ♦ Facsimile: (617) 253-1301 ♦ Electronic Mail: mgreene@rle.mit.edu

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Prof. David E. Pritchard

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Research Laboratory of Electronics
Massachusetts Institute of Technology
77 Massachusetts Avenue
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13. ABSTRACT (Maximum 200 words)

We are developing new measurement techniques using coherent atom optics (such as beam-splitters, mirrors and lenses) to manipulate matter waves. We operate an atom interferometer, which splits deBroglie waves of matter into two physically separate paths and then recombines the waves to make interference fringes of matter. By measuring the contrast and phase of these interference fringes, our experiments are extremely sensitive to any interactions affecting the atoms.

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Annual Technical Report to ONR:

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Principle Investigator: David E. Pritchard

Forward

We are developing new measurement techniques using coherent atom optics (such as beam-splitters, mirrors and lenses) to manipulate matter waves. We operate an atom interferometer, which splits deBroglie waves of matter into two physically separate paths and then recombines the waves to make interference fringes of matter. By measuring the contrast and phase of these interference fringes, our experiments are extremely sensitive to any interactions affecting the atoms.

List of Figures

During this grant period we completed experiments on quantum decoherence, we have nearly finished an experiment on the matter-wave index of refraction, and we invented an improved measurement technique for atomic polarizability. These three research topics and a summary of the most important results are each explained in a sub-section below.

Decoherence

Decoherence is of fundamental theoretical importance for any quantum system interacting with its environment, and it is the major practical obstacle for large scale quantum computing. Our three recent experiments on decoherence test various scaling laws and provide new insight on wave-particle duality.

We studied decoherence in a system which is simple enough that the measured decoherence rate constant can be compared with ab initio calculations [KRC01] for the first time. This offers a benchmark measurement supporting several quite general theories of decoherence (many of which are directly relevant to quantum computation efforts). This recent experiment broadens the scope of our earlier, pioneering work on decoherence due to spontaneous photon emission [CHL95] by exploring decoherence as a function of the number, n, of photons scattered from each atom. Scattering multiple photons causes the same time-evolution of decoherence as interaction with a thermal bath, and is theoretically similar to any situation where the quantum system undergoes multiple independent scattering events.

The heart of this experiment is the principle of complementarity, which forbids simultaneous observation of wave and particle behavior. Our results confirm that the atomic interference (a manifestly wave-like behavior) is destroyed when the separation of the interfering paths, d, exceeds the wavelength of the probe, λ, (i.e. when it is possible to identify which path the atom traversed). Building upon the simple framework of the single-photon which-way experiment, we can easily derive the effect of continuous atom-light interaction involving many independent scattered photons. Figure 1 summarizes our results.

In the photon scattering experiment, decoherence depends on quantum entanglement between an atom (which is referred to as the "system") and the final momentum of the scattered photons (which collectively constitute the "environment"). In a second experiment, we replaced the random process of photon scattering with a deterministic momentum transfer caused by a diffraction grating. In this case, loss of contrast still occurs, but less abruptly as a function of separation, and this de-phasing arises from a qualitatively different reason. The atom's own longitudinal momentum plays the role of the environment. This mechanism may not qualify as quantum decoherence, because entanglement between two degrees of freedom of a single particle can never demonstrate what Einstein referred to as "spooky action at a distance".

Finally, we studied how an atom's internal state controls its own decoherence rate. Because the same environment that causes decoherence can also optically pump atoms into an internal state which will no longer scatter laser light, the atom's internal (electronic) state can determines the rate of external (spatial) decoherence.

Matter-wave index of refraction

We measured the matter-wave index of refraction for Na waves passing through targets of Ar, N2, Kr, and Xe gasses. In analogy to the transmission of light through materials, atom-waves passing through a dilute gas suffer a dispersive phase shift, We measure the ratio, $\rho = Re(n)/Im(n)$, of phase shift to amplitude attenuation.

We have observed oscillations in ρ as a function of Na velocity. Much theoretical work has been stimulated by our earlier measurements of ρ [SCE95], and there are conflicting predictions on the dependence of ρ on velocity [ADV95, FYK97]. The variance in the predictions arises because ρ is very sensitive to both long-range (>5 Angstrom) and medium-range (0.5 to 5 Angstrom) atom-atom interactions. By studying oscillations in ρ (which have never before been observed) we hope to constrain the theoretical models of van der Waals molecular potentials.

Electronic velocity multiplexing

We have prototyped a novel atom optic, which we are using for dispersion compensation. Velocity multiplexing using a pair of slotted wheels was previously proposed for improving experiments on dispersive interactions [HPC95]. While this could improve

absolute measurements of atomic polarizability [ESC95], spinning mechanical disks have disadvantages such as: vibrations, reliability, mechanical timing alignment, and a reduction of atom flux to ¼. Our new dispersion compensation method uses two compact electric-field gradients, which can be electronically pulsed to give a variable phase shift to atoms with different velocity. This technology should retain 100% of the atom flux, be widely tunable, and ultimately improve measurement accuracy for any dispersive phase shift. We have used two gradient regions to compensate for the dispersion caused by an electric field applied to one arm of the interferometer. This causes a contrast revival at an electric filed which normally reduces contrast to an unusable level.

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[ADV95] E.Audouard, P. Duplaa, and J. Vigue, "Glory and Resonance Effects in the Index of Refraction for Atomic Waves", Europhys. Lett. 32 pg 397 (1995)

[SCE95] J. Schmiedmayer, M.S. Chapman, C.R. Eksrom, T.D.Hammond, S.Wehinger, and D.E. ritchard, "Index of Refraction of Various Gases for Sodium Matter Waves", Phys. Rev. Lett. 74 pg 1043 February (1995)

[CHL95] M.S. Chapman, T.D. Hammond, A.L. Lenef, J.Schmiedmayer, R.A.Rubenstein, E.Smith, and D.E.Pritchard, "Photon Scattering from Atoms in an Atom Interferometer: Coherence Lost and Regained" Phys. Rev. Lett. 75 pg. 3783 (1995)

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[HPC95] T.D. Hammond, D.E. Pritchard, M.S. Chapman, A. Lenef, and J. Schmiedmayer,. "Multiple Velocity Selection for Precision Matter Wave Interferometry", Appl. Phys. B 60, 193 (1995)

Publications in Peer-Reviewed Journals in the past year

D.A. Kokorowski, A.D. Cronin, T.D. Roberts, and D.E. Pritchard, "From Single to Multiple-Photon Decoherence in an Atom Interferometer" PRL 86 2191, (2001), quant-ph/0009044

D. E. Pritchard, A. D. Cronin, S. Gupta, D.A.Kokorowski, "Atom Optics: Old Ideas, Current Technology, and New Results" Ann. Phys. 10 35, (2001)

S. Gupta, A.E. Leanhardt, A.D. Cronin, and D.E. Pritchard, "Coherent Manipulation of Atoms with Standing Light Waves" C.R. Acad.Sci. IV 479, (2001)

Recent Conference Presentations with Abstracts:

Colloquium, University of Connecticut, Storrs CT, November 20, 2000
Colloquium, University of Puget Sound. Tacoma, WA November 27, 2000
Coherent Spectroscopy Seminar, University of Washington, Seattle, WA, Nov. 29,00
Physics Colloquium, Whitman College, Walla Walla, WA, December 1, 2000
100 Years of Quantum Theory Conference, Vienna, Germany, December 2000
Physics of Quantum Electronics Conference, Snowbird, UT, January 8, 2001
DAMOP 2001: APS meeting, London, Ontario May 2001
Colloquium, University of Rochester, November 2001

Popular Press on Our Research:

Articles on recent work performed by our interferometer group have appeared in
AIP Physics Bulletin on Physics News, P.F. Schewe, B. Stein, Jan. 4, 1996;
T. Sudbery, Nature **379** (1996) 403;
J. Hecht, Laser Focus World **32** (1996) 20 ;
D. H. Freedman, Discover **17** (1996) 58;
Physics Today **50** (1997) 9;
C. Seife, Science **275** (1997) 931;
P. Yam, Scientific American, June 1997, 124.
R. Pool, Discover, December 1997, 103.,
M. Browne, NY Times (Science Section) August 15, 1995. *It's a Molecule. No, it's more like a wave.*

Scientific personell supported by this project in the past year:

GRADUATE (Ph.D.): Tony Roberts (PhD expected early 2002), David Kokorowski 2001
UNDERGRADUATE (B.S.): Peter Finin 2001, Martin Tiberg 2001
POSTDOCTORAL ASSOCIATIONS: Alex Cronin

FIGURES:

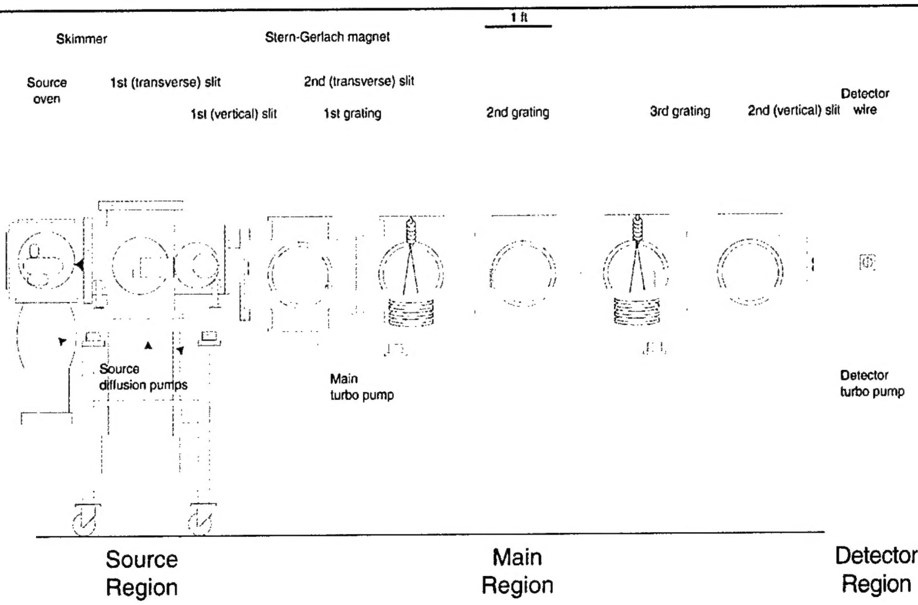

Figure 1: Improved apparatus. The critical components of the atom interferometer are suspended on a vibrationally isolated platform (ndicated as a solid grey) within the center of the vacuum system.

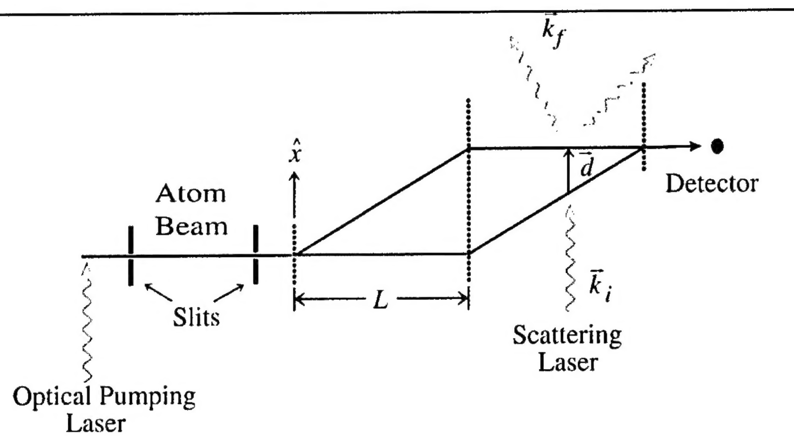

Figure 2: Decoherence experiment diagram. Scattering photons from atoms inside the interferometer destroys the coherence between the two paths of the interferometer – thus reducing fringe contrast

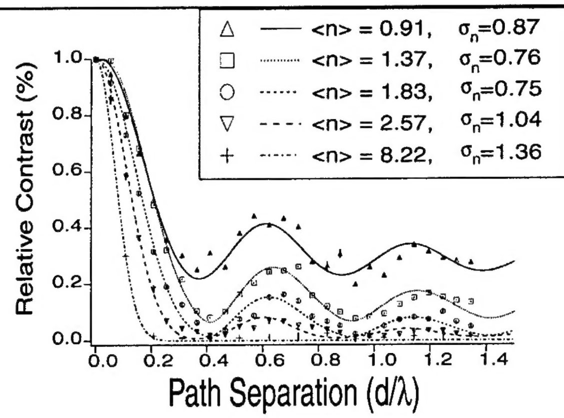

Figure 3: Decoherence data from multiple photon scattering. The relative contrast diminishes as a complicated function of path separation (d) when the numbrer of photons scattered from each atom (n) is less than two or three. With larger n, the contrast decays as a gaussian function of d.

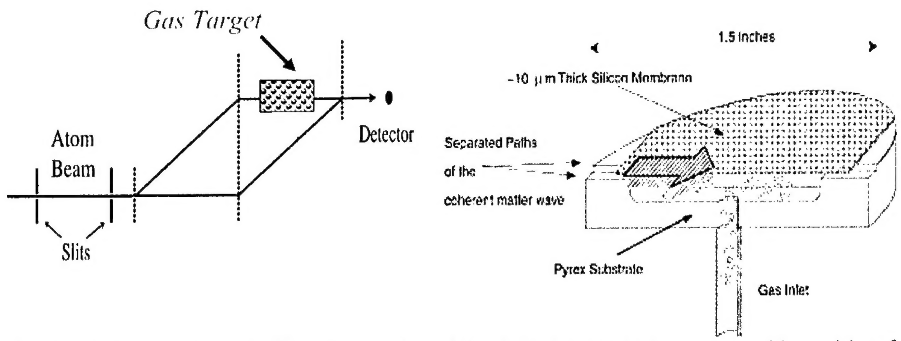

Figure 4: Index of refraction experiment. The two paths of the interferometer pass on either side of a thin barier, and gas is introduced into one side.

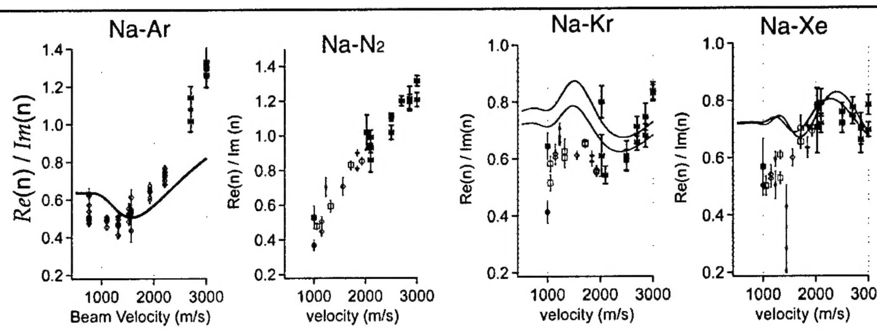

Figure 5: Matter wave index of refraction at different velocities. The variation in the index of refraction indicates a first-ever observation of glory oscillations in the phase shift.

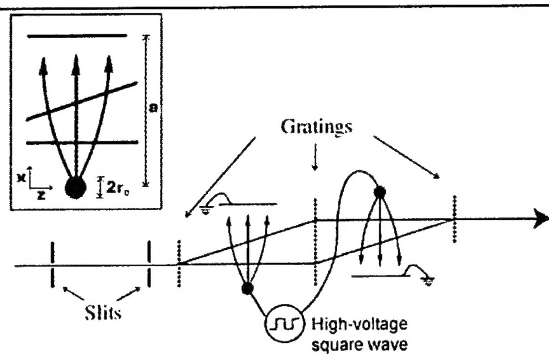

Figure 6: Dispersion compensators. Two regions of electric field gradient each can produce a 180 degree phase change in the interference fringes. By pulsing the voltage on and off in time, we create a situation where contrast revivals can occure. Soon we will use this to improve precision measurements with atom interferometers.

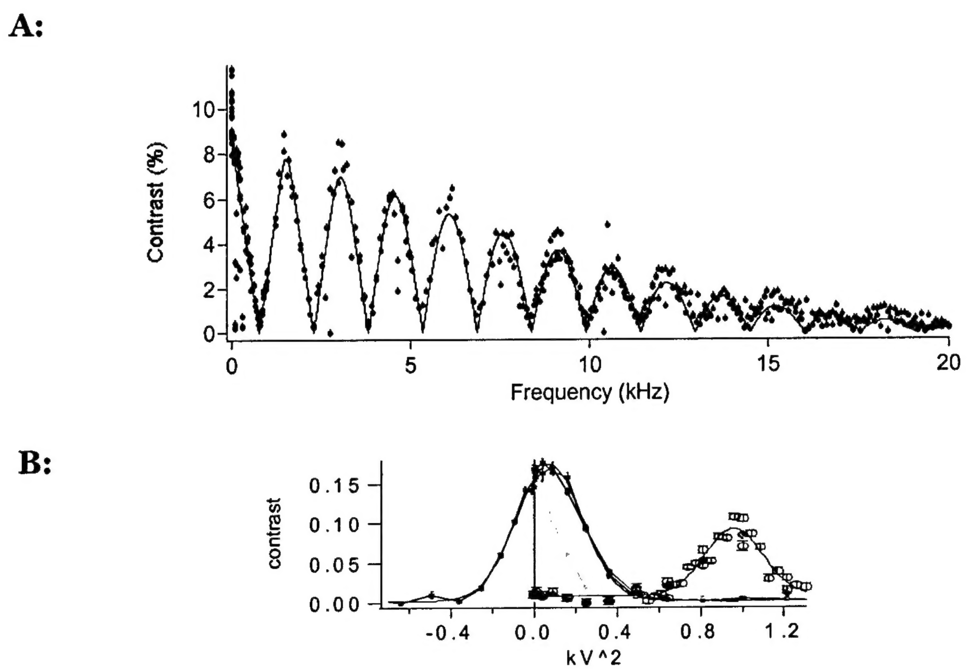

Figure 7A: Contrast revivals as a function of frequency indicate the dispersion compensators are working properly in the absence of an applied electric field. 7B: The single contrast revival as a function of applied electric field will allow us to measure atomic polarizability with higher accuracy than ever before.

ATTACHMENT NUMBER 1

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